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Radon-Progeny Exposure and Lung Cancer Risk in a Cohort of Newfoundland Fluorspar Miners

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Although radon is a well-established lung carcinogen, there are uncertainties concerning the exposure–response relationship, whether exposures in early life are particularly hazardous, and how smoking affects the risks associated with radon exposure. A cohort study of the mortality experience of 1,743 underground fluorspar miners and 321 surface workers from 1950 to 1984 reported previously has been extended to include 6 additional years of follow-up (1985–1990). A statistically significant relationship was noted between radon-progeny exposure and risk of lung cancer mortality. Our analysis found no effect for age at first exposure. Attained age was strongly predictive of excess relative risk (ERR) per working level month (WLM) of radon exposure, falling from 0.025 for those aged less than 50 years to 0.002 for those 70 years or older. An inverse exposure-rate effect was also observed, wherein for equal total exposure, a high exposure rate (and short duration) is less harmful than a low exposure rate (and long duration). The ERR/WLM increased from 0.0019 for exposures of less than 10 years to 0.0076 for exposures of 20 or more years. The analysis of time-since-exposure windows revealed a greater ERR/WLM for exposures received in more recent periods, similar to the result for time since last exposure. Excess relative risks per WLM were higher for current smokers than for nonsmokers (never and former smokers). Analyses were consistent with a multiplicative relationship between radon-progeny exposure and current smoking and the risk of lung cancer. The assessment of radon exposure and lung cancer risk should incorporate the effects of exposure rate, time since exposure, smoking status and attained age.

INTRODUCTION

An increased risk of lung cancer is well established among underground miners exposed to radon and its progeny. Epidemiological studies of miner cohorts have been used to set regulatory standards for radon in mines, and to estimate the risk of lung cancer in the general population, who may be exposed to radon in their homes. However, uncertainties remain concerning the exposure–response relationship, whether exposures in early life are particularly hazardous and how smoking interacts with radon exposure.

The underground mining of fluorspar in St. Lawrence, Newfoundland, began in 1936 and continued until 1978. In 1960, tests revealed the presence of radon in the large quantity of water that seeped into the mines. Beginning in 1960, mechanical ventilation was installed in the mines and radon-progeny levels fell to well below the permissible standards of the time. This report updates the analysis published in 1988 (*1*) by including further data on cigarette smoking and 6 additional years of mortality follow-up and by treating cigarette smoking status as a time-dependent variable.

METHODS

The initial cohort of miners consisted of 2,111 underground miners and 550 surface workers employed by either the St. Lawrence Fluorspar Company or Newfoundland Fluorspar Limited. Miners who lacked adequate personal identifying information or who had died before 1950 were dropped from the analysis. Most of those excluded from analysis were short-term workers employed during World War II. The remaining 1,772 underground miners and 352 surface workers were those analyzed in the 1988 report (*1*). For the present analysis, a further 29 underground miners and 31 surface workers who were born before 1900 for whom no death information was available were dropped. The final cohort of miners included 1,743 underground miners and 321 millers or surface workers.

Estimates of working level months (WLM) according to year, mine and occupation between 1933 and 1960 were obtained by adjusting 1960 levels to reflect working conditions of the mines and mine architecture. One working level (WL) is the concentration of short-lived radon daughters in a liter of air which would give rise to 1.3×10^5 MeV of α-particle radiation. One working level month is equivalent to exposure to one working level for 170 h. Cumulative exposures were expressed in working level months.

The Atomic Energy Control Board of Canada (AECB)[1] estimated historical radon-progeny levels based on a review of mine maps, commission hearings, recollections of working conditions by former workers, inspectors' reports and the 80 radon-progeny samples taken in 1960 prior to the

[1]D. A. Corkill and A. B. Dory, A retrospective study of radon daughter concentrations in the workplace in the fluorspar mines of St. Lawrence, Nfld. Atomic Energy Control Board, Ottawa, 1984.

introduction of mechanical ventilation at 50 different underground locations in the principal mine then in operation. Values ranged between 0.4 and 193 WL in unventilated areas and from below the level of detection to 12 WL in ventilated portions of the mine. From 1961 to 1967, annual surveys revealed mean radon-progeny levels below 0.3 WL. Based on 400 to 700 samples per year, only about 3% of the readings were in excess of 1 WL.[2] From 1968 until 1978, when the last mine closed, daily exposures for each worker were recorded based on radiation levels in the place worked on a given day (mean = 0.17 WL during 1969–1978).[3] Based on previous studies and analysis of the current data, a lag interval of 5 years was incorporated into the calculation of cumulative exposure (*2*). Thus radon exposure within the previous 5 years was assumed to be unrelated to risk of lung cancer. The mean cumulative exposure for underground workers was 382.8 WLM over an average of 5.7 years of exposure.

A survey was conducted by Health Canada in 1993 to determine changes in smoking behavior between 1978 (the date of the last previous survey) and 1993. Previous surveys to ascertain smoking behavior were conducted in 1960, 1966 and 1970 in St. Lawrence, Newfoundland, by Health and Welfare Canada and in 1978 by the Atomic Energy Control Board. Some information on smoking was available for 65% of the cohort exposed to radon. Previous cohort studies collected information on smoking at only one time, or over a limited period. With the current survey, we had information on smoking spanning over 30 years for many miners. For 46% of the miners exposed to radon, data on smoking were available from all surveys for which the miners were alive and thus could be asked. Individuals without information on smoking were retained for all analyses except those involving smoking.

The mortality experience of the cohort was determined by tracing all members manually through the Canadian Mortality Database operated by Statistics Canada. The linkage was performed by employees who were blind to exposure status. Copies of microfilmed death certificates were obtained and the underlying causes of death were coded according to the 8th revision of the International Classification of Diseases by the Nosology Reference Centre of Statistics Canada. As with previous analyses, persons not found were assumed to be alive for the purposes of analysis.

Mortality was analyzed from the beginning of 1950 to the end of 1990. Mortality before 1950 was not examined to facilitate comparisons with results published previously. Furthermore, the quality of Newfoundland death certificates before 1950 precluded their use (*3*).

Statistical Analysis

Cigarette smoking status was treated as a time-dependent variable, and underground miners were categorized as never, former or current smokers. The year of initiation of smoking and, where applicable, the year of cessation of smoking were determined from surveys of smoking conducted in 1993, 1978, 1970 and 1966. Where discrepancies existed, the most recent survey conducted was deemed the most reliable. Attained age was categorized as <40, 40–44, 45–49,...,70–74 and 75+ years. Age at first exposure to radon was categorized as <25, 25–<40 and 40+ years. Similarly, time since last exposure was categorized as <10, 10–<20, 20–<30 and 30+ years. Calendar period was categorized as follows: 1950–1959, 1960–1969, 1970–1979 and 1980–1990.

Previous studies (*2*) have shown that for equal total exposure, workers exposed for longer durations at lower rates are at higher risk for lung cancer than workers exposed for shorter durations at higher rates. The pattern is often referred to as an inverse exposure-rate (or protraction enhancement) effect. To assess the inverse exposure-rate relationship, exposure duration was defined as a time-dependent covariate using the following categories: <10, 10–<20 and 20+ years.

[2]Digest of Newfoundland Fluorspar Limited submission to the Royal Commission investigating health and radiation conditions and matters involving workmen's compensation, St. Lawrence, Newfoundland, April, 1968.

[3]Report of the Royal Commission respecting radiation, compensation and safety at the fluorspar mines, St. Lawrence, Nfld, pp. 17–32, 1969.

Poisson regression methods were used to fit relative risk (RR) and absolute (excess) risk (ER) models. To examine the effects of attained age, cigarette smoking status, age at first exposure to radon, time since last exposure and exposure duration on the relationship between exposure to radon progeny and lung cancer risk, a linear excess relative risk model (I), RR = 1 + β WLM, was initially fitted. In this model, β represents the increase in ERR per unit increase in cumulative WLM, with the intercept constrained to 1.0. The significance of attained age, age at first exposure, smoking status, time since last exposure and exposure duration were assessed separately by comparing model (I) with models of the form $1 + \beta_j$WLM, where j denotes the categories of attained age, smoking status, age at first exposure and exposure duration. A test of the homogeneity of the β_j was obtained from the difference in the deviances of the two models, which under the null hypothesis of no variation in the β_j is distributed asymptotically as a χ^2 random variable with $n - 1$ degrees of freedom (df), where n is the number of categories. In the absolute (excess) risk model, the rate takes the form $r(x,w) = r_0(x) + \xi$WLM, where r_0 is the background rate of lung cancer, and the parameter ξ is the excess lung cancer rate per WLM, i.e. the ER/WLM. The likelihood-based 95% confidence limits for β (ERR/WLM) and ξ (ER/WLM) were calculated.

As in previous analyses[2] (*2*), cumulative WLM exposure was partitioned into time-since-exposure windows. For each year of age, cumulative exposure was expressed as

$$w = w_{5-14} + w_{15-24} + w_{25+},$$

where w_{5-14} was the cumulative exposure received 5–14 years prior to the specific age, w_{15-24} was the cumulative exposure received 15–24 years prior, etc. In the person-years table, a different time-dependent dimension was established for each exposure window. Model (I) was extended as follows: $RR = 1 + \beta_j WLM^*$, where $WLM^* = \theta_1 w_{5-14} + \theta_2 w_{15-24} + \theta_3 w_{25+}$. In related analyses, age-at-exposure and dose-rate windows were examined. Cumulative WLM exposure was partitioned into exposures received prior to and after age 35, and into exposures of up to four WLM/year and four or more WLM/year. The θ parameters represent weights for components of WLM in the defined windows.

To examine smoking and radon-progeny exposure, relative risks were estimated within categories of WLM and smoking status. As only four lung cancer deaths occurred among never-smokers, our analyses combined former and never-smokers into one category. The joint relative risk (RR) association for categories of smoking status (s) and WLM (w) was modeled as

$$RR(s,w) = \phi_{s,w},$$

where $\phi_{s,w}$ represents seven relative risk parameters (two smoking levels and four WLM categories, with the referent group being nonsmokers at the lowest WLM category, and set to one). This "full" model was compared to the multiplicative RR model,

$$RR(s,w) = \phi_s \times \phi_w,$$

and to the additive RR model,

$$RR(s,w) = \phi_s + \phi_w - 1.$$

The multiplicative and additive models include four RR parameters. A geometric mixture was also fitted. The model was

$$RR(s,w) = [\phi_s \times \phi_w]^{\lambda} [\phi_s + \phi_w - 1]^{1-\lambda},$$

where λ is a scale parameter. This model includes the multiplicative model (λ = 1) and the additive model (λ = 0) as special cases. In the analysis, all RRs were adjusted for categories of attained age and calendar period as described previously.

TABLE I
Mortality among Underground Newfoundland Fluorspar Miners, 1950–1990

Cause of death	Observed	Expected[a]	SMR	95% CI
All causes	576	482.05	1.20	1.10–1.30
Infective and parasitic disease	17	8.60	1.98	1.23–3.17
Neoplasms	228	117.40	1.94	1.71–2.21
Buccal cavity and pharynx	6	2.51	2.39	1.10–5.21
Salivary gland	2	0.21	9.74	2.67–35.50
Digestive tract	43	46.25	0.93	0.69–1.25
Trachea, bronchus and lung	138	32.08	4.30	3.64–5.08
Prostate	10	7.12	1.41	0.76–2.59
Urinary tract	11	5.84	1.88	1.05–3.37
Brain, nervous system	3	2.84	1.06	0.36–3.11
Lymphatic and hematopoietic	6	6.73	0.89	0.41–1.94
Endocrine, nutritional, metabolic	3	8.18	0.37	0.12–1.08
Mental diseases	5	3.49	1.43	0.61–3.35
Diseases of nervous system	3	7.06	0.42	0.14–1.25
Diseases of circulatory system	209	230.94	0.90	0.79–1.04
Ischemic heart disease	149	146.26	1.02	0.87–1.20
Cerebrovascular disease	16	40.87	0.39	0.24–0.64
Nonmalignant respiratory disease	40	33.50	1.19	0.88–1.63
Chronic bronchitis, emphysema and asthma	23	10.61	2.17	1.44–3.25
Silicosis and anthrasilicosis	7	0.12	60.96	29.53–125.9
Digestive system diseases	10	14.71	0.68	0.37–1.25
Genitourinary diseases	2	7.81	0.26	0.07–0.93
Symptoms ill-defined	1	8.47	0.12	0.02–0.67
Accidents, poisonings and violence	56	38.30	1.46	1.13–1.90
Traffic accidents	14	10.83	1.29	0.77–2.17
Accidental falls	7	2.78	2.52	1.22–5.19
Accidental drownings	8	7.25	1.10	0.56–2.18
Suicide	5	4.97	1.01	0.43–2.36

[a]Expected number of deaths based on male age-specific Newfoundland mortality between 1950–1990.

RESULTS

The mortality experience of 1,743 underground miners and 321 surface workers was examined. Among the underground miners, 576 deaths and 48,189 person-years were observed between 1950 and 1990 (Table I). Of these, 228 deaths were from cancer, of which 138 were from lung cancer. Observed numbers of deaths from cancers of the lung, buccal cavity, salivary gland and urinary tract were significantly elevated when compared to the mortality rates for Newfoundland males between 1950 and 1990. A significant excess number of deaths was also noted for infectious and parasitic diseases (primarily tuberculosis), chronic obstructive lung disease, silicosis and accidental falls. Only eight lung cancer deaths were observed among surface workers.

Lung cancer mortality by cumulative WLM is presented in Table II. Relative risk estimates for categorical WLM estimates, adjusted for attained age and period, increased with increasing cumulative exposure. Using continuous WLM, the excess relative risk estimate was 0.0070/WLM (95% CI = 0.0044–0.0114) (Fig. 1). The absolute excess risk coefficient was estimated as 6.4 (95% CI = 5.0–8.0) deaths per WLM per million person-years. The deviances of the RR and ER models were comparable (523.2, 1010 *df* and 517.4, 1010 *df*, respectively).

Attained age modified the ERR/WLM, falling from 0.025 for those aged less than 50 to 0.0021 for those 70 years or older (Table III). ERR/WLM did not vary by age at first exposure (Table IV). The excess relative risk of lung cancers among miners who had not been exposed in the last 30 years approached baseline rates (ERR/WLM = 0.0007) (Table V).

Excess relative risk per WLM increased with increasing duration of exposure (Table VI), indicating that risk per unit exposure decreased with increasing exposure rate. Further evidence of this can be seen by examining ERR/WLM by dose-rate windows. Although the test for homogeneity was not statistically significant, ERR/WLM were markedly higher for dose rates under 4 WLM/year compared to those of 4 WLM/year or greater.

The analysis of age-at-exposure windows suggested a decreased ERR/WLM for exposures occurring prior to age 35 (Table VII); however, this result was not statistically significant ($P = 0.16$). The analysis of time-since-exposure windows revealed a greater ERR/WLM for exposures received in more recent periods (Table VII), similar to the result for time since last exposure.

TABLE II
Lung Cancer Mortality by Cumulative Radiation Exposure, Newfoundland Fluorspar Cohort, 1950–1990

Cumulative exposure (WLM)[a]	Mean exposure (WLM)	Person-years	Lung cancer deaths	Relative risk[b]	95% CI
0	0	14,751	8	1.0	
>0–<25	4.66	17,711	18	1.81	0.77–4.25
25–<200	90.07	9,878	15	2.15	0.91–5.10
200–<500	329.52	6,962	17	3.34	1.43–7.78
500–<1000	698.84	3,224	12	4.96	2.02–12.19
1000–<1500	1238.26	1,685	18	14.25	6.16–32.94
1500–<2000	1742.46	1,221	18	19.17	8.29–44.36
2000–<2500	2184.44	688	12	22.47	9.14–55.27
2500–<3500	3006.58	565	13	30.30	12.49–73.47
3500+	3913.33	346	15	49.97	21.01–118.9

[a]Working level months. A lag interval of 5 years was incorporated into the calculation of cumulative exposure.
[b]Relative risks were adjusted for attained age and calendar period.

Some information on smoking was available for 65% of the exposed miners. Almost 90% of those of known smoking status were either current or former cigarette smokers. However, the prevalence of current cigarette smokers has decreased over the period between the last two surveys. Based on the 1978 AECB and 1993 Health Canada smoking surveys, 32% of those smoking in 1978 had quit smoking by 1993. Only three members of the 1993 cohort questioned about their smoking status began smoking after 1978.

Table VIII displays relative risks based on additive and multiplicative models that account for smoking status. By rescaling the RRs for smokers given in the tables (calculated by dividing the RRs cited in the table by 1.68, the RR for the lowest radon exposure category for smokers), it is possible to compare smokers and nonsmokers directly. Among nonsmokers, RRs are 1.0, 4.8, 5.2 and 5.2, while the RRs for smokers are 1.0, 2.2, 7.6 and 12.4. The patterns suggest that there is a greater gradient in the effects of WLM among smokers (i.e. a supra-multiplicative effect). Models with WLM and cigarette smoking status were fitted to formally assess the joint association. The geometric mixture model fit the data as well as the full model, and the estimate of λ indicated a greater than multiplicative association for WLM and smoking. The multiplicative model was consistent with the data ($P = 0.20$ when testing for lack of fit relative to the full model), while the additive model was rejected ($P = 0.05$). The ERR/WLM was higher for current smokers than nonsmokers ($P = 0.03$) (Table IX).

DISCUSSION

In this cohort, significantly elevated numbers of deaths were noted for cancers of the lung, buccal cavity and pharynx (primarily due to salivary gland cancer), and the urinary

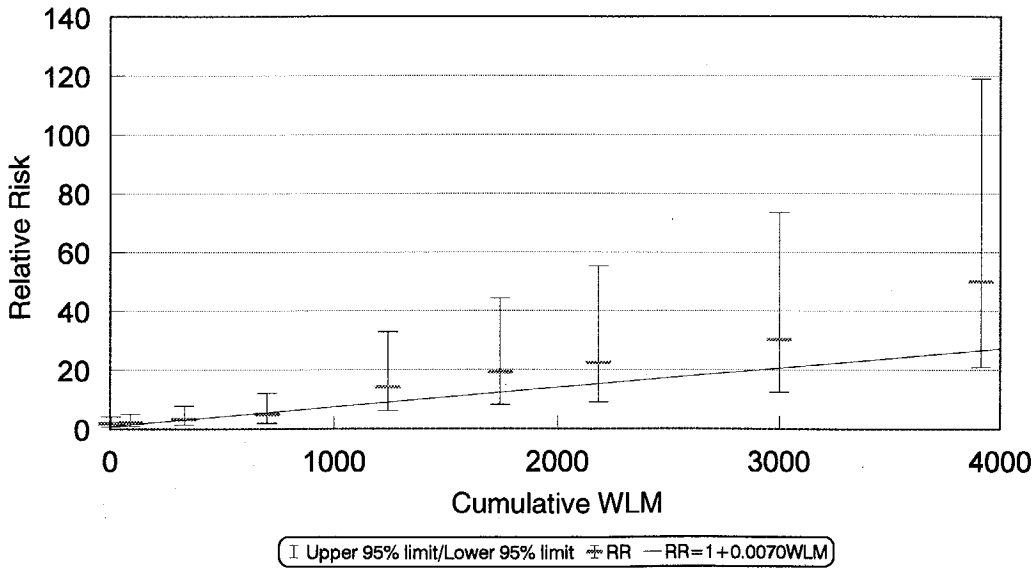

FIG. 1. Estimated relative risk of lung cancer, by cumulative radon-progeny dose, Newfoundland fluorspar miners, 1950–1990. RRs are plotted at the mean WLM for each category and were adjusted for age and period.

TABLE III
Excess Relative Risk of Lung Cancer[a] per WLM, by Attained Age, Newfoundland Fluorspar Cohort, 1950–1990

Attained age	Lung cancer deaths	ERR/WLM	95% CI	P^b
<50	39	0.0253	0.0093,0.1020	0.0077
50–<60	55	0.0069	0.0032,0.0160	
6–<70	37	0.0032	0.0012,0.0081	
70+	15	0.0021	0.0001,0.0093	
All ages	146	0.0070	0.0044,0.0114	

[a]Background rates adjusted for attained age and period. A lag interval of 5 years was incorporated into the calculation of cumulative exposure.
[b]*P* value for test of homogeneity of ERR/WLM.

tract, as well as silicosis, accidental falls, and infectious and parasitic diseases (primarily tuberculosis). Patterns of mortality were similar to those noted in the previous analysis (*2*), with the exception that a significantly increased risk was now observed for urinary tract cancer. A pooled study of 11 miner cohorts (*4*) failed to note excesses for cancers of the buccal cavity and pharynx, or urinary tract, suggesting that radiation exposure is not a likely explanation for the elevated risks in our cohort.

Elevated mortality from silicosis reflects the high levels of silica dust in the mines[4] prior to the improvement in ventilation instituted in 1960. There is evidence that silica is a carcinogen in the lungs of humans (*5*). It is therefore probable that if adjustment for silica exposure had been possible, it would have resulted in lower estimates of the effect of radon progeny.

As expected, risk of dying of lung cancer was found to be strongly associated with cumulative exposure to radon progeny. The ERR coefficient for the cohort (0.0070 per WLM) suggests that the exposure required to double the risk of lung cancer is 144 working level months. The ERR/WLM from the previous follow-up was 0.009/WLM, resulting in a similar doubling dose. In a joint analysis of 11 miner cohorts (*2*), the excess relative risk coefficient was estimated to be 0.0049 per WLM for all 11 cohorts, and 0.0076 per WLM for the fluorspar cohort. The estimate for all 11 cohorts combined was that risk doubled after an exposure of 204 WLM. However, because risk varies strongly with attained age and exposure rate, and to a lesser extent with time since last exposure, a single summary risk measurement may be misleading.

The present analysis relied primarily upon the relative risk model compared to the absolute risk model. There was no intrinsic reason to prefer the RR model to the ER model. An emphasis was placed on the RR model because of the ease of incorporating temporal effects and to aid comparability to the 11-cohort study (*2*).

Excess relative risks per WLM were found to decrease with attained age. This agrees with the findings of Lubin *et al.* in their 11-cohort analysis (*2*). The declining ERR/WLM with attained age indicates that a constant RR model (in cumulative exposure) does not describe the data adequately. In addition, evidence from miner studies also indicates that a simple absolute excess risk model does not describe the data adequately (*6*). Thus lung cancer mortality appears to be intermediate between a simple proportional increase (ERR/WLM) and a simple additive increase (ER/WLM) above the background risk of miners who were not exposed to radon.

Excess relative risk per WLM increased with increasing duration of exposure, suggesting that those at lower exposures for a longer period have a greater risk than those exposed to an equivalent exposure but at higher rates over a shorter period. It has been suggested that the inverse exposure-rate effect, reported from studies of other miners (*2*, *7*) and animals (*8*), may result either from less cell killing at lower exposure rates (*2*), or because extended duration of exposure allows for greater cell proliferation (*9*).

[4]J. P. Windish and H. P. Sanderson, Dust hazards in the mines of Newfoundland. Newfoundland Fluorspar Limited, St. Lawrence, Newfoundland. Occupational Health Division, Department of National Health & Welfare, Ottawa, 1958.

TABLE IV
Excess Relative Risk of Lung Cancer[a] per WLM, by Age at First Exposure, Underground Fluorspar Miners, Newfoundland, 1950–1990

Age at first exposure	Lung cancer deaths	ERR/WLM	95% CI	P^b
<25	64	0.0074	0.0043–0.0133	0.26
25–<40	51	0.0054	0.0025–0.0123	
40+	23	0.0095	**–0.0337	
All exposed	138	0.0067	0.0039–0.0119	

[a]Background rates adjusted for age and period. A lag interval of 5 years was incorporated into the calculation of cumulative exposure.
[b]*P* value for test of homogeneity of ERR/WLM.
**Convergence could not be attained for lower 95% CI bound.

TABLE V
Excess Relative Risk of Lung Cancer[a] per WLM, by Time since Last Exposure, Underground Fluorspar Miners, Newfoundland, 1950–1990

Time since last exposure (years)	Lung cancer deaths	ERR/WLM	95% CI	P^b
0–<10	58	0.0112	0.0064–0.0199	<0.0001
1–<20	44	0.0075	0.0040–0.0137	
20–<30	24	0.0026	0.0008–0.0060	
30+	12	0.0007	**–**	
All exposed	138	0.0067	0.0039–0.0119	

[a]Background rates adjusted for age and period. A lag interval of 5 years was incorporated into the calculation of cumulative exposure.
[b]P value for test of homogeneity of ERR/WLM.
**Convergence could not be attained for 95% CI bounds.

However, it is possible that the inverse exposure-rate effect is at least in part the result of greater exposure misclassification at higher exposure rates than at lower exposure rates. The effect of non-differential misclassification should be to bias risk estimates toward the null, therefore preferentially reducing the risk estimates for high exposure rates compared to lower exposure rates. In the current study, high exposure rates occurred prior to 1960. Because data for exposure prior to 1960 were extrapolated, there is likely to have been a much higher degree of misclassification of these exposures compared to exposures after 1960.

There were too few lung cancer deaths among miners first exposed after 1960 to examine whether the inverse exposure-rate effect was attenuated. It is not known to what extent this potential bias may have produced the observed inverse exposure-rate effect in the Newfoundland cohort. The 11-study analysis by Lubin and colleagues (*2*) found that the inverse exposure-rate effect did not vary significantly by calendar period of first exposure.

Our analysis found no effect for age at first exposure, as did the 1988 fluorspar miner report (*1*) and the combined 11-cohort study (*2*). Although there is evidence of an increased relative risk of certain cancers resulting from exposure to γ radiation in childhood compared to exposure later in life (*10*), there is no direct supporting evidence for high-linear energy transfer (LET) radiation and lung cancer.

Thomas *et al.* (*11*), analyzing data from the Colorado Plateau miners cohort, concluded that the interaction between smoking and radiation may be intermediate between additive and multiplicative. This finding was supported by the multi-cohort analysis by Lubin *et al.* (*2*). The present analysis supports a multiplicative interaction between smoking and radon exposure, but it was hampered by the small number of lung cancer deaths occurring among never-smokers. As well, detailed cigarette smoking histories, including start and stop dates, were available for only slightly less than half of the cohort. Nevertheless, it appears that the effect of radon-progeny exposure in former smokers was reduced compared to current smokers.

Our analysis of the fluorspar cohort noted an excess relative risk for lung cancer of 0.0070 per WLM. This is slightly lower than that observed by Lubin and colleagues (*2*) (0.0076) in their analysis of the fluorspar cohort. The difference resulted from the current analysis having been based on a longer follow-up time (1990 compared to 1984), with the resulting increase in time since last exposure.

TABLE VI
Excess Relative Risk of Lung Cancer[a], per WLM (ERR/WLM), by Exposure Duration and by Dose-Rate Windows, Underground Fluorspar Miners, Newfoundland, 1950–1990

Exposure duration (years)	Lung cancer deaths	ERR/WLM	95% CI	P^b
0–<10	4	0.0019	0.0004–0.0048	<0.0001
10–<20	65	0.0067	0.0040–0.0116	
20+	19	0.0076	0.0039–0.0143	
Overall	138	0.0067	0.0039–0.0119	
Dose-rate windows	**(θ)**	**ERR/WLM**	**95% CI**	**P^b**
<4 WLM/year	1.0	0.38	0.097–1.22	0.31
4+ WLM/year	0.024	0.0092	0.0047–0.022	

[a]Background rates adjusted for age and period. A lag interval of 5 years was incorporated into the calculation of cumulative exposure as well as duration of exposure.
[b]P value for test of homogeneity of ERR/WLM.

TABLE VII

Excess Relative Risk of Lung Cancer[a] per WLM, Age-at-Exposure and Time-since-Exposure Windows, Underground Fluorspar Miners, Newfoundland, 1950–1990

	Age-at-exposure windows		
	<35 years (θ_1)	≥35 years (θ_2)	P^c
	1.0	1.56	0.16
ERR/WLM[b]	0.0058	0.0090	
95% CI	(0.0030–0.0110)	(0.0041–0.0202)	

	Time since exposure windows (years)			
	5–14 (θ_1)	15–25 (θ_2)	25+ (θ_3)	P^c
	1.0	0.59	0.21	<0.0001
ERR/WLM[b]	0.0143	0.0084	0.0030	
95% CI	(0.0052–0.0366)	(0.0035–0.0184)	(0.0012–0.0065)	

[a]Background rates adjusted for age and period. A lag interval of 5 years was incorporated into the calculation of cumulative exposure.
[b]Estimated ERR/WLM(%) for exposure occurring prior to age 35 or for exposures at 5–14 years since exposure.
[c]*P* value for test of homogeneity of estimates of age-at-exposure or time-since-exposure effects.

From a public health perspective, the exposure–response relationship below 100 WLM is of greatest importance, given the present Canadian standard of 4.0 WLM per year for uranium miners (*12*). Fortunately, few workers are exposed to anywhere near the current standard of 4.0 WLM per year (*12*). Evidence from this study and others indicates that the effect of low-exposure-rate radiation may be greater per unit exposure than that of high-exposure-rate radiation; however, the 11-study pooled analysis of miners exposed to radon noted that there was a diminution of the inverse dose-rate effect under 50 WLM (*7*).

After adjustments for attained age and period, the current analysis suggested that 69% of the lung cancer in this cohort could be attributed to the effects of radon-progeny exposure. The current analysis noted a lower attributable risk (AR) among never and former smokers (AR = 0.56) than current smokers (AR = 0.78), but the difference was not statistically significant (results not shown). Lubin *et al.* (*2*) found a lower AR among never-smokers in this cohort

TABLE VIII

Relative Risk of Lung Cancer and Fitted Models, Underground Newfoundland Fluorspar Miners, by Cumulative Radon-Progeny Exposure and Smoking Status (All RR Adjusted for Age and Calendar Period)

		Cumulative WLM						
Smoking status		<500	500–<1500	1500–<2500	2500+	RR	RR[a]	RR[b]
Non-current	Deaths	6	7	4	2			
	RR	1.0	4.80	5.17	5.22	1.0	1.0	1.0
Current	Deaths	19	12	19	21			
	RR	1.68	3.75	12.78	20.88	1.89	1.76	1.70
Total	Deaths	25	19	23	23			
	RR	1.0	2.81	6.38	11.18			
	RR[a]	1.0	2.76	6.97	10.97			
	RR[b]	1.0	3.65	9.48	15.53			

Model	Change in deviance	Degrees of freedom	P^c
Full	—	271	—
Mixture ($\lambda = 4.3$)	3.9	273	0.15
Multiplicative	4.7	274	0.20
Additive	8.0	274	0.05
WLM	9.5	275	0.05
Smoking status	72.4	277	0.00
Background	78.7	278	0.00

Notes. *n* = number of cases of lung cancer. RR is the relative risk estimate fitted with the full model.
[a]Relative risk estimate fitted with an additive model.
[b]Relative risk estimate fitted with a multiplicative model.
[c]*P* value of model fit relative to full model.

TABLE IX
Excess Relative Risk of Lung Cancer[a], per WLM, by Cigarette Smoking Status, Underground Fluorspar Miners of Known Smoking Status, Newfoundland, 1950–1990

Smoking status	Lung cancer deaths	ERR/WLM	95% CI	P^b
Non-current	19	0.0025	0.0006–0.0093	0.03
Current	71	0.0055	0.0024–0.0168	
Overall	90	0.0046	0.0020–0.0144	

[a]Background rates adjusted for age and period. Smoking status was categorized as a time-dependent variable.
[b]P value for test of homogeneity of ERR/WLM.

compared to smokers (0.65 compared 0.86), although higher ARs for never-smokers compared to smokers have been reported for other studies (*2*). In the analysis of Lubin *et al.*, the combined AR for all studies reporting information on smoking were 0.73 and 0.39 for never-smokers and smokers, respectively (*2*).

Because risk varies according to several factors, a single summary risk estimate is felt to be misleading. The effects of the risk factors analyzed are consistent with results obtained from the analyses of other mining cohorts. Our analyses suggest that, ideally, the assessment of radon exposure and lung cancer risk should incorporate the effects of exposure rate, time since exposure, smoking status and attained age.

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